

FIG. 3

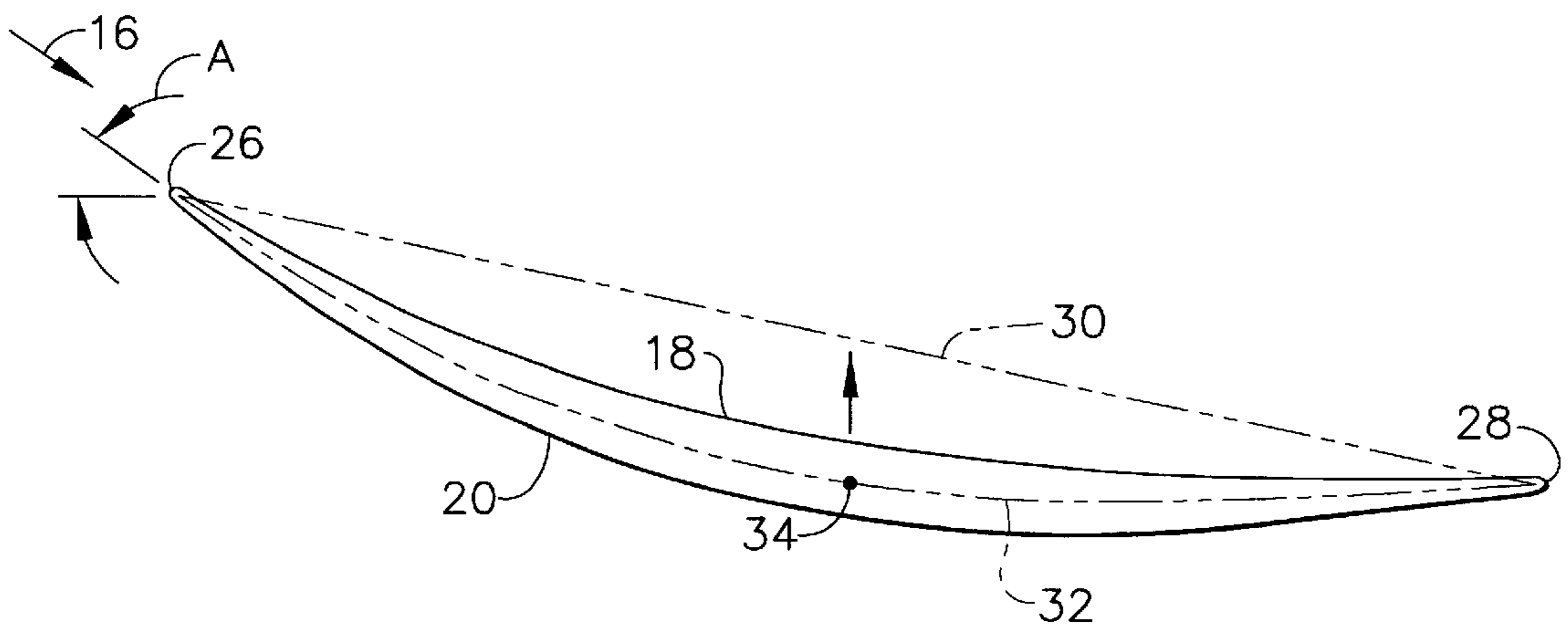


FIG. 4



**BOWED COMPRESSOR AIRFOIL**

The US Government may have certain rights in this invention pursuant to Contract No. N00019-96-C-0176 awarded by the US Department of the Navy.

**BACKGROUND OF THE INVENTION**

The present invention relates generally to gas turbine engines, and, more specifically, to compressors or fans therein.

In a turbofan aircraft gas turbine engine, air is pressurized in a fan and compressor during operation. The fan air is used for propelling an aircraft in flight. The air channeled through the compressor is mixed with fuel in a combustor and ignited for generated hot combustion gases which flow through turbine stages that extract energy therefrom for powering the fan and compressor.

A typical turbofan engine includes a multistage axial flow compressor which pressurizes the air sequentially to produce high pressure air for combustion. Fundamental in compressor design is efficiency in compressing the air with sufficient stall margin over the entire flight envelope of operation from takeoff, cruise, and landing.

However, compressor efficiency and stall margin are normally inversely related with increasing efficiency typically corresponding with decrease in stall margin. The conflicting requirements of stall margin and efficiency are particularly demanding in high performance military engine applications which require high level of stall margin in conjunction with high compressor efficiency.

Maximizing efficiency of compressor airfoils is primarily effected by optimizing the velocity distributions over the pressure and suction sides of the airfoil. However, efficiency is typically limited in conventional compressor design by the requirement for a suitable stall margin. Any further increase in efficiency results in a reduction in stall margin, and, conversely, further increase in stall margin results in decrease in efficiency.

High efficiency is typically obtained by minimizing the wetted surface area of the airfoils for a given stage to correspondingly reduce airfoil drag. This is typically achieved by reducing airfoil solidity or the density of airfoils around the circumference of a rotor disk, or by increasing airfoil aspect ratio of the chord to span lengths.

For a given rotor speed, this increase in efficiency reduces stall margin. To achieve high levels of stall margin, a higher than optimum level of solidity may be used, along with designing the airfoils at below optimum incidence angles. This reduces axial flow compressor efficiency.

Increased stall margin may also be obtained by increasing rotor speed, but this in turn reduces efficiency by increasing the airfoil Mach numbers, which increases airfoil drag.

Accordingly, typical compressor designs necessarily include a compromise between efficiency and stall margin favoring one over the other.

It is, therefore, desired to further improve both compressor efficiency and stall margin together for improving gas turbine engine compressor performance.

**BRIEF SUMMARY OF THE INVENTION**

A compressor airfoil includes pressure and suction sides extending from root to tip and between leading and trailing edges. Transverse sections have respective chords and camber lines. Centers of gravity of the sections are aligned along a bowed stacking axis either tangentially, axially, or both, for improving performance.

**BRIEF DESCRIPTION OF THE DRAWINGS**

The invention, in accordance with preferred and exemplary embodiments, together with further objects and advantages thereof, is more particularly described in the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 is an isometric view of a portion of a gas turbine engine compressor rotor stage having bowed airfoils extending radially outwardly from an integral rotor disk in accordance with an exemplary embodiment of the present invention.

FIG. 2 is a forward-facing isometric view of one of the airfoils illustrated in FIG. 1 and taken generally along line 2—2 in a tangential and radial plane.

FIG. 3 is a side elevation view of one of the airfoils illustrated in FIG. 1 and taken generally along line 3—3 circumferentially projected in an axial and radial plane.

FIG. 4 is a radial transverse section through an exemplary portion of the airfoil illustrated in FIG. 3 and taken along line 4—4.

**DETAILED DESCRIPTION OF THE INVENTION**

Illustrated in FIG. 1 is a portion of an annular rotor blisk 10 defining one stage of a multistage axial flow compressor for a gas turbine engine. The blisk includes a plurality of circumferentially spaced apart rotor blades or airfoils 12 extending radially outwardly from the perimeter of an integral rotor disk 14 forming a one-piece unitary assembly. The blisk may be manufactured using conventional milling and electrochemical machining.

Alternatively, the airfoils may be formed with integral dovetails for being removably mounted in corresponding dovetail slots in the perimeter of discrete rotor disk in another conventional configuration.

During operation, the blisk rotates in the exemplary clockwise direction illustrated in FIG. 1 for pressurizing air 16 as it flows between the adjacent airfoils. The airfoils are aerodynamically configured in profile for maximizing the efficiency of air compression while also providing a suitably high stall margin for enhancing performance of the compressor. The blisk 10 illustrated in FIG. 1 is only one of several stages of rotor airfoils which may be configured in accordance with the present invention for enhancing compressor performance by increasing together both efficiency and stall margin.

Notwithstanding the conventional compromise made between aerodynamic efficiency and stall margin, modern computer software is conventionally available for solving three-dimensional (3D) viscous flow equations for evaluating airfoil performance. The resulting airfoils generally have distinctive 3D configurations which differ significantly over conventional airfoils which vary little in radial section over the spans thereof.

FIG. 1 illustrates a specifically bowed airfoil 12 uncovered from 3D analysis having improved performance for increasing both efficiency and stall margin not previously possible.

The rotor disk 14 has three orthogonal axes including axial X, tangential or circumferential Y, and radial Z. The axial axis X extends in the downstream direction relative to the flow of air 16 through the compressor. The tangential axis Y extends in the direction of rotation of the disk and airfoils. And, the radial axis Z extends radially outwardly from the perimeter of the disk for each of the airfoils thereon.



Each airfoil **12** includes a generally concave pressure side **18** and a generally convex suction side **20** extending radially or longitudinally from a root or hub **22** integrally joined with the perimeter of the disk to a radially outer tip **24**. The two sides extend chordally or axially between leading and trailing edges **26, 28** from root to tip.

In accordance with one feature of the present invention, the airfoil suction side **20** is laterally or tangentially bowed along the trailing edge **28** near or adjacent the root **22** at the intersection with the disk perimeter. Flow separation of the air at this location may be substantially reduced or eliminated for both increasing blade efficiency and improving stall margin.

The suction side trailing edge is bowed primarily only in the tangential direction as illustrated in FIG. 2. In the side projection of the axial and radial plane X-Z illustrated in FIG. 3, the suction side bow is imperceptible. However, the airfoil may also be axially bowed as illustrated in FIG. 3 for further improvements in performance as later discussed hereinbelow.

The airfoil illustrated in FIGS. 1-3 is defined by a plurality of radially or longitudinally stacked transverse sections, one of which is illustrated in FIG. 4. Each section has an aerodynamic profile defined by respective portions of the pressure and suction sides **18,20** extending between the leading and trailing edges **26,28**. Each profile is defined by a straight chord **30** extending axially between the leading and trailing edges, and an arcuate camber line **32** which is a meanline spaced equidistantly between the pressure and suction sides from leading to trailing edge. The camber line **32** has a camber angle A relative to the axial axis X which varies between the leading and trailing edges, and is typically generally parallel with the incident air **16** at the airfoil leading edge.

Each airfoil section also has a center of gravity **34** which is aligned radially along the longitudinal span of the airfoil in a bowed stacking axis **36** as illustrated in FIG. 1. The stacking axis **36** in conjunction with the shapes of the corresponding airfoil sections including their chords **30** and camber lines **32** permit 3D definition of the airfoil for enhanced performance in accordance with the present invention.

More specifically, the stacking axis **36** illustrated in FIG. 1 has two orthogonal components including a tangential stacking axis **36a** illustrated in FIG. 2 and an axial stacking axis **36b** illustrated in FIG. 3. As shown in FIG. 2, the tangential stacking axis **36a** is non-linear or bowed adjacent the airfoil root **22** to bow the suction side **20** of the airfoil near the trailing edge root or hub.

The tangential stacking axis **36a** initially leans onward or in the forward direction of rotation of the airfoils and disk from the root **22** toward the pressure side **18** of the airfoil. The axis **36a** then leans hindward or backward, which is opposite to the direction of rotation of the airfoils and disk, toward the suction side **20** adjacent the tip **24**. Correspondingly, camber of the airfoil transverse sections adjacent the root varies in turn to bow the suction side thereat.

The bow of the tangential stacking axis **36a** and the corresponding shapes of the transverse sections are selected for substantially reducing or eliminating flow separation of the air along the suction side near the airfoil hub at the trailing edge.

The bowed stacking axis permits the trailing edge **28** as illustrated in FIGS. 1 and 2 to be oriented substantially normal to the root of the bowed suction side **20** and leans

hindward thereabove. The trailing edge **28** intersects the perimeter or platform of the rotor disk at an intersection angle B which would otherwise be significantly acute without the trailing edge bow. Computer analysis indicates that acute trailing edge intersection angles promote hub flow separation which decreases efficiency of the airfoil. The suction side bow reduces the acuteness of the intersection angle B for correspondingly reducing flow separation, with an attendant increase in efficiency. The bowed stacking axis permits centrifugal loads developed during operation to slightly straighten the airfoil and introduce local compressive bending stress which locally offsets centrifugal tensile stress.

Accordingly, the preferentially bowed airfoil reduces flow separation at the hub, and is limited only by the degree of stacking axis bow which may be introduced with acceptable bending stresses during operation. Improved hub airflow increases airfoil efficiency without compromising stall margin.

Aerodynamic sweep is a conventional parameter for evaluating performance of a compressor airfoil. In accordance with another feature of the present invention, means are provided for limiting aft aerodynamic sweep of the airfoil **12** between the leading and trailing edges. Aft sweep can adversely affect stall margin, and selectively limiting aft sweep can enhance the stall margin.

Aft sweep of the airfoil **12** illustrated in FIG. 3 may be limited by selectively bowing the axial stacking axis **36b**, and also by selectively varying the chord distributions of the transverse sections.

For example, aft sweep may be limited by configuring the airfoil leading edge **26** to have an axially coplanar radially outer or outboard portion which includes the tip **24**. And, the remaining radially inner or inboard portion of the leading edge **26** is inclined axially forwardly to the root **22** from the outboard portion.

FIG. 3 illustrates an axial projection of the airfoil **12** from its suction side **20** and shows a straight leading edge outboard portion which is preferably positioned at a constant axial location. The inboard portion of the leading edge **26** leans forward as the airfoil root is approached relative to the radial line illustrated in phantom. Aerodynamic aft sweep of the airfoil is thusly limited at the leading edge from the root to the tip of the airfoil.

As shown in FIG. 3, the outboard and inboard portions of the leading edge **26** intersect or transition from each other at about the midspan of the airfoil. In a preferred embodiment, the midspan transition is within the range of about 40% span height to about 60% span height. Both airfoil efficiency and stall margin may further be increased by this preferred leading edge configuration.

Aft aerodynamic sweep may be further limited by preferentially configuring the airfoil trailing edge **28** as illustrated in FIG. 3. The axial stacking axis **36b** in conjunction with corresponding chord lengths may be used to control trailing edge configuration. In a preferred embodiment illustrated in FIG. 3, the trailing edge **28** has an axially coplanar inboard portion including the root **22**, and an outboard portion inclined axially forwardly to the tip **24** from the inboard portion.

The inboard and outboard portions of the trailing edge **28** intersect or transition from each other radially inwardly between the midspan of the airfoil and the root **22**. In a preferred embodiment, this trailing edge inboard transition is within the range of about 15% span height to about 25% span height. The trailing edge configuration is thusly defined



by holding a constant axial position of the trailing edge from the root **22** over the minority inboard portion of the span height, at which the majority outboard portion of the trailing edge projects or is inclined forwardly towards the tip **24** relative to the radial line illustrated in phantom. Again, aft aerodynamic sweep is limited for correspondingly increasing airfoil efficiency and stall margin.

Since the stacking axis includes both tangential and axial components, the tangential component may be used to advantage to introduce the bowed suction side **20** near the trailing edge at the root as illustrated in FIGS. **1** and **2** for the advantages described above. Correspondingly, the axial component of the stacking axis may be selected for limiting the aft sweep along both the leading and trailing edges **26,28** as illustrated in FIG. **3**.

And, quite significantly, the axial contour of the airfoil cooperates with the tangential contour for yet further reducing or eliminating flow separation.

The stacking axis is configured in conjunction with the shapes of the individual transverse sections of the airfoil including the distribution in length of the chords **30** and the camber of the camber lines **32**. And, the specific configuration of the stacking axis may also be controlled for limiting centrifugally generated bending stresses in the airfoil within acceptable limits.

Accordingly, the two components of the stacking axis and the shape of the airfoil transverse sections may be additionally configured based on **3D** viscous flow analysis to increase both airfoil efficiency and stall margin resulting in the distinctive **3D** configuration illustrated in the figures.

The degree of suction side bow and limitation of aft sweep along the leading and trailing edges may be adjusted in different combinations for different airfoil configurations to vary the benefits of increased airfoil efficiency and corresponding stall margin. The resulting airfoil **12** may thusly be designed for truly three dimensional performance attributable to modern advances in computational analysis which makes such improvements possible.

While there have been described herein what are considered to be preferred and exemplary embodiments of the present invention, other modifications of the invention shall be apparent to those skilled in the art from the teachings herein, and it is, therefore, desired to be secured in the appended claims all such modifications as fall within the true spirit and scope of the invention.

Accordingly, what is desired to be secured Letters Patent of the United States is the invention as defined and differentiated in the following claims in which we claim:

**1.** A compressor airfoil for a rotor disk having axial, tangential, and radial orthogonal axes, comprising:

pressure and suction sides extending radially from root to tip, and axially between leading and trailing edges; transverse sections having respective chords and camber lines extending between said leading and trailing edges, and centers of gravity aligned in a bowed stacking axis; and

said suction side being bowed in said tangential axis along said trailing edge adjacent said root for reducing flow separation thereat.

**2.** An airfoil according to claim **1** wherein said stacking axis comprises two orthogonal components including a tangential stacking axis and an axial stacking axis, and said tangential stacking axis is bowed adjacent said airfoil root to bow said suction side thereat.

**3.** An airfoil according to claim **2** wherein said tangential stacking axis initially leans onward from said root toward

said pressure side, and then leans hindward toward said suction side adjacent said tip, and camber of said sections adjacent said root varies to bow said suction side thereat.

**4.** An airfoil according to claim **3** wherein said onward lean is in the direction of rotation of said airfoil atop said disk, and said hindward lean is opposite to said direction of rotation.

**5.** An airfoil according to claim **3** wherein said trailing edge is oriented substantially normal to said root at said bowed suction side, and leans hindward thereabove.

**6.** An airfoil according to claim **1** further comprising means for limiting aft aerodynamic sweep of said airfoil between said leading and trailing edges.

**7.** An airfoil according to claim **6** wherein:

said stacking axis has two orthogonal components including a tangential stacking axis and an axial stacking axis; and

said sweep limiting means comprise bowing said axial stacking axis.

**8.** An airfoil according to claim **7** wherein said sweep limiting means further comprise varying chord distributions of said transverse sections.

**9.** An airfoil according to claim **8** wherein said sweep limiting means further comprise said leading edge having an axially coplanar outboard portion including said tip, and an inboard portion inclined forwardly to said root from said outboard portion.

**10.** An airfoil according to claim **9** wherein said outboard and inboard leading edge portions transition at about a midspan of said airfoil.

**11.** An airfoil according to claim **10** wherein said midspan transition is within the range of 40% span height to about 60% span height.

**12.** An airfoil according to claim **8** wherein said sweep limiting means further comprise said trailing edge having an axially coplanar inboard portion including said root, and an outboard portion inclined forwardly to said tip from said inboard portion.

**13.** An airfoil according to claim **9** wherein said inboard and outboard trailing edge portions transition inboard between a midspan of said airfoil and said root.

**14.** An airfoil according to claim **13** wherein said inboard transition is within the range of about 15% span height to about 25% span height.

**15.** An airfoil according to claim **8** wherein said sweep limiting means further comprise:

said leading edge having an axially coplanar outboard portion including said tip, and an inboard portion inclined forwardly to said root from said outboard portion; and

said trailing edge has an axially coplanar inboard portion including said root, and an outboard portion inclined forwardly to said tip from said trailing edge inboard portion.

**16.** An airfoil according to claim **15** wherein:

said outboard and inboard leading edge portions transition at about a midspan of said airfoil; and

said inboard and outboard trailing edge portions transition inboard between said midspan and said root.

**17.** An airfoil according to claim **16** wherein:

said leading edge midspan transition is within the range of about 40% span height to about 60% span height; and

said trailing edge inboard transition is within the range of about 15% span height to about 25% span height.

**18.** A compressor airfoil for a rotor disk having axial, tangential, and radial orthogonal axes, comprising:

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pressure and suction sides extending radially from root to tip, and axially between leading and trailing edges; transverse sections having respective chords and camber lines extending between said leading and trailing edges, and centers of gravity aligned in a bowed stacking axis; said suction side being bowed along said trailing edge adjacent said root for reducing flow separation thereat; and

wherein said stacking axis has two orthogonal components including a tangential stacking axis and an axial stacking axis, and said tangential stacking axis is bowed adjacent said airfoil root to bow said suction side thereat.

**19.** A compressor airfoil for a rotor disk having axial, tangential, and radial orthogonal axes, comprising:

pressure and suction sides extending radially from root to tip, and axially between leading and trailing edges;

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transverse sections having respective chords and camber lines extending between said leading and trailing edges, and centers of gravity aligned in a bowed stacking axis; and

means for limiting aft aerodynamic sweep of said airfoil between said leading and trailing edges.

**20.** An airfoil according to claim **19** wherein said stacking axis is bowed in said tangential axis along said trailing edge adjacent said airfoil root to bow said suction side thereat.

**21.** An airfoil according to claim **20** extending radially outwardly from said rotor disk in a unitary blisk, and said suction side is bowed adjacent said disk for reducing hub flow separation thereat.

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